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PARTICULATE EMISSIONS OF A DUAL FUEL CATERPILLAR 3208 ENGINE

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DISCLAIMER

This study was carried out with the cooperation of the Department of Energy, Mines and Resources. However, the views expressed in the report are those of the author and do not necessarily reflect the views of the Department.

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1.0 INTRODUCTION

1.1 Importance of Particulate Measurements

Recently, the United States Environmental Protection Agency (EPA) announced new regulations intended to control the emissions of particulates from diesel engine exhaust. The new regulations for particulates are shown in table 1 for light and heavy duty diesel engines [1].

Diesel emissions are composed of unburned carbon particles (soot), hydrocarbons attached to the carbon particles, NO_x, SO_x and CO [2]. The particulate emissions are of special concern because most are small enough to be inhaled and deposited in the lungs. Toxic hydrocarbons and gases can also be carried in to the lungs because they easily stick to the particulates. In addition, diesel engines typically produce 50 to 100 times more particulates than gasoline engines [2].

Thus, particulate emissions have become a concern for diesel engine manufacturers and are an important factor to consider when evaluating diesel and dual fuel engines. There has been some speculation that the use of natural gas in diesel engines in dual fuel configuration can dramatically reduce the particulate emissions, since only a fraction of the normal diesel amount is burned [3]. It is the purpose of this work to determine if this speculation is in fact valid.

In this report the particulate emissions have been determined for a Caterpillar 3208 diesel engine operating on both diesel and dual fuel. All data reported in this work are based on steady state particulate tests. While this methodology is different from the transient test methodology required for certification purposes, it is widely used by diesel engine manufacturers for comparative analysis.

1.2 Available Options for Particulate Measurements

The facilities specified by the Environmental Protection Agency for proper measurement of particulate emissions are prohibitively expensive. In addition, the requirements call for a very long (40 ft) dilution tunnel to ensure complete mixing of raw exhaust gas and dilution air and cooling of the mixture at the primary filter below the recommended 51.7 C [1].

Although it would be ideal to use a full scale EPA dilution tunnel for particulate measurements, substantial information can be obtained by constructing a mini-dilution tunnel and measuring steady state particulate emissions. There have been many mini-dilution tunnels reported in the literature [4], and data have been collected and compared to that of large EPA tunnels. These tunnels use flow disturbance techniques for promoting homogeneous mixing of dilution air and exhaust gas. It has been reported that particulate mass emissions measured in mini-tunnels correlate well with those measured in total exhaust dilution tunnels at steady state operating conditions [5]. However, for emissions measurements over EPA test cycles, a constant flow sampling unit is required since the exhaust flow rates are continually changing. There is also some discrepancy between cycle averaged particulate emissions measured in a mini-tunnel and in total exhaust dilution systems [4]. It is thus almost impossible to correlate steady state emissions to EPA cycle averaged results. For comparison purposes, however, the mini tunnel would provide enough information.

The requirements at B.C. Research were to compare the particulate emissions between diesel and dual fuel configurations as well as to optimize dual fueling strategies in order to minimize these emissions. For this type of work, a mini dilution tunnel with steady state measurements capabilities is well suited. The disadvantages of using a mini tunnel and performing steady state measurements are the inability to draw direct quantitative comparisons with EPA specifications, but a great deal of information can be inferred from comparison with diesel engine emissions.

2.0 MINI DILUTION TUNNEL DESIGN

The Cummins Engine Company provided the plan of a mini tunnel that they developed for measuring steady state particulate emissions. As can be seen on Figure 1, this plan included the layout of the tunnel and specifications for the equipment used. The B.C. Research tunnel design was based on this information with some significant modifications to equipment and layout. In addition, Dr. Shimpi from Cummins provided valuable advice on building and testing procedures.

The resulting design was a mini tunnel which deviated from the EPA specifications mainly by its size and the absence of a constant flow sampling system. EPA specifications for filtration techniques were followed, but the recommended 70 mm filter arrangement was found to be too expensive and like Cummins, we used a standard 47 mm filter. The EPA code was adhered to whenever possible in the design of the tunnel.

3.0 EXPERIMENTAL SYSTEM

3.1 Dilution Tunnel

The dilution tunnel is typically a tube in which exhaust gases are inducted and mixed with clean dilution air and from which a sample is drawn for filtration. A drawing of the B.C. Research mini dilution tunnel is shown in Figure 2 and a schematic of the entire system is illustrated in Figure 3.

Dilution air is first drawn through a MSA 85175 mining grade filter to remove any particulates. A smooth transition from the filter diameter to the tunnel diameter reduces the friction losses. A butterfly valve, downstream of the air inlet, is used to control the airflow in the tunnel, and thus control the dilution ratio. The tunnel itself is straight stainless steel 76.4 mm (3") I.D. pipe.

Raw exhaust gas is channeled to the tunnel through a 19.0 mm (3/4 ") stainless steel tube and introduced in the center of the air stream in the tunnel. The raw gases are drawn due to the vacuum caused by the flowing air stream. A high temperature

stainless steel ball valve was installed at the exhaust manifold on the advice of Dr. Shimpi, Cummins Engine Company. This valve further controls the dilution ratio.

A continuous sample of diluted mixture is extracted from the tunnel 1.5 m (5 ft) downstream of the mixing point. The dilution sample is collected by a 19 mm (3/4 ") stainless tube located at at the center of the tunnel. The tube edges were chamfered to minimize drag and recirculation of the gas as it is drawn through the pipe. A second 19 mm stainless steel ball valve is located in the sample line directly upstream of the filters. A shielded thermocouple measures the temperature near the sample point. The 1.64 m (5 ft) length of pipe enables adequate mixing and cooling of the mixture.

All parts in contact with raw or diluted exhaust upstream of the filters were made of stainless steel to avoid corrosion or other reactions between the gases and the equipment.

The blower that draws the dilution mixture is located at the very end of the tunnel. This centrifugal fan has a capacity of 200 cfm at 2" H20. The fan exhausts the gas to the room ventilation system.

3.2 Filtration System

The filtration system is shown schematically in figure 2. The diluted sample is drawn through the sample line, passes through the 19 mm (3/4") ball valve, followed by the main and back-up filters. These are Pallflex T60A20 teflon coated glass fiber filters, as recommended in the EPA specifications. The 47 mm diameter filters are held in place by stainless steel filter holders. The two filters are 3 " apart and inclined as recommended in the EPA specs.

Directly downstream of the secondary filters a thermocouple is mounted in the flow stream to monitor the filter temperature. Downstream of the filters, the gas flow rate is measured by a Rockwell R-200 (bellows type) test meter. Pressure and temperature are measured upstream of the gas meter to reference the apparent flow rate to standard conditions.

The sample is drawn by a Thomas model 2737c positive displacement diaphragm pump which has the ability to deliver 2.36 l/s (5 SCFM) against a 105 kPa (15 psi) pressure difference. Directly upstream of the pump, a valve is used to set the sample flow rate. The gas is then exhausted to the room ventilation system.

3.3 CO_2 Measurement

In order to determine the dilution ratio, the concentration of CO_2 is measured in the ambient air, raw exhaust and diluted mixture. For this purpose, the heated exhaust line used for NOx and hydrocarbon emissions measurement was used. The sample was routed to the CO_2 analyzers in the gasoline emissions bench. A diagram of the CO_2 measurement system is shown in figure 3. A three way stainless steel valve was used to switch sampling between the exhaust manifold and the dilution tunnel.

All CO_2 measurements were made using a Beckman Model #864 analyzer. This analyzer determines carbon dioxide concentration by measuring the absorbtion of infra-red light by the exhaust sample and comparing it to a reference cell. The typical response time of this analyzer was 0.5 seconds.

4.0 MEASUREMENT OF PARTICULATE EMISSIONS

4.1 Development of the Procedures

The EPA procedures were followed for filter manipulation, conditioning and weighing. The optimum filter loading was deduced from the EPA specifications based on the loading for a 70 mm filter. For all our work a 49 mm filter was used. Thus the optimum filter loading for the smaller diameter units used was determined in the following way:

$$5.3 \text{ mg} \times (49/70)^2 = 2.6 \text{ mg}$$

This filter loading is the determining factor in the selection of dilution ratio and sample flow rates. Since the upper sample flow rate was fixed at 3 SCFM, the test time was varied for optimum filter loading. All the test procedures used in this work are modeled on the EPA specifications.

4.2 Test Methodology

The technique consists of drawing a stream of exhaust gas from the exhaust manifold, diluting it with clean air until the mixture is homogeneous and cooled, and finally filtering the diluted mixture through ultrafine filters which are weighed before and after the test.

The steps are the following:

1) Stabilize engine operating condition

   The engine was run at the desired speed and load until all parameters have stabilized.

2) Set dilution ratio

   The butterfly and exhaust ball valve were adjusted until the dilution ratio was set according to preliminary calculations described below.

3) Install filter holders

   The filters had been pre-conditioned for 24 hours, and weighed as indicated in EPA specifications. They were then mounted in the holder unit (see Figures 4 & 5) in the controlled environment. The holder unit is sealed at both ends until it is mounted in the sample line (see Figure 6).

4) Start test

   The initial gas meter reading was noted. The sample pump was started and run at a rate of between 2 and 3 SCFM. The timer was started as soon as the sample started flowing through the filters.

5) Collect diluted exhaust for 2 minutes for diesel. The test time was variable for dual fuel operation.

6) End Test

After the test period, the sample pump was stopped. The final gas meter reading was noted.

7) Remove Filter Unit

The unit should was sealed and taken to the laboratory for conditioning and weighing.

8) Condition and Weigh Filters

5.0 DETERMINATION OF DILUTION RATIO AND PARTICULATE CONCENTRATION

5.1 Particulate Concentration in Exhaust Gases

Figure 7 is a schematic of the dilution tunnel set-up and indicates the quantities discussed below. Part of the exhaust gases are admitted to the dilution tunnel where they are mixed with ambient air. The various quantities shown in this diagram are defined below:

m_e = mass flow rate of exhaust gas

m_a = mass flow rate of ambient dilution air

m_d = mass flow rate of dilute mixture

m_p = mass flow rate of exhaust supply line entering the dilution tunnel

m_{part_s} = mass flow rate of particulates in the sample line

The quantities measured during the test are:

$C_{co_{2_a}}$ = CO_2 concentration in ambient air

$C_{co_{2_e}}$ = CO_2 concentration in raw exhaust

$C_{co_{2_d}}$ = CO_2 concentration in dilution mixture

Q_s = Volumetric flow rate of Sample

T_s = Temperature upstream of sample flow meter

P_s = Pressure upstream of sample flow meter

m_{filter} = mass accumulated in filters

t = test duration

The following equations can be written to describe the system:

Conservation of Mass

$$m_a + m_p = m_d \qquad (1)$$

a = ambient air

p = particulate supply

d = dilution mixture

It is assumed that there is no chemical reaction between the raw exhaust gases and the dilution air. Thus, the number of moles of each species and the total number of moles is conserved.

Conservation of CO_2

$$n_{co_{2_a}} + n_{co_{2_p}} = n_{co_{2_d}} \qquad (2)$$

Conservation of Number of Moles

$$n_a + n_p = n_d \qquad (3)$$

The dilution ratio is defined as the ratio of molar flow rates of diluted to exhaust gas, or the same ratio of volumetric flow rates referenced to standard temperature and pressure.

$$D_R = \frac{n_d}{n_p} = \frac{Q_{d_{@STP}}}{Q_{p_{@STP}}} \qquad (4)$$

The concentration of CO_2 is defined as the number of moles of CO_2 to the total number of moles. Using equations 1, 2 and 3 the dilution ratio can be expressed as a function of the CO_2 concentrations in the ambient air, raw exhaust and dilution mixture:

$$D_R = \frac{C_{co_{2a}} - C_{co_{2e}}}{C_{co_{2a}} - C_{co_{2d}}} \qquad (5)$$

The mass flow rate of particulates flowing through the sample line is :

$$m_{part_s} = \frac{m_{filter}}{t} \qquad (6)$$

The volumetric flow rate of sample at standard temperature and pressures is:

$$Q_{@STP} = Q_s \frac{273\ K}{T_s} \frac{P_s}{101.3\ kPa} \qquad (7)$$

Q_s is the apparent flow rate measured at the gas meter.

$$Q_s = \frac{Q_2 - Q_1}{t} \qquad (8)$$

The ratio of particulates to total volume in the sample line is the same at that in the dilution tunnel

$$\frac{m_{part_s}}{Q_{s_{@STP}}} = \frac{m_{part_d}}{Q_{d_{@STP}}} \quad (9)$$

Since no particulates are introduced with the dilution air, the mass flow rate of particulates in the supply line is identical to that in the dilution tunnel.

$$m_{part_d} = m_{part_p} \quad (10)$$

The ratio of particulates to volumetric flow rate in the raw exhaust is the also the same as in the supply line.

$$\frac{m_{part_e}}{Q_e} = \frac{m_{part_p}}{Q_p} \quad (11)$$

Using equations 4, 9, 10 and 11 the mass flow rate of particulates can be determined as is shown below:

$$m_{part_e} = \frac{D_R \quad m_{part_s} \quad Q_e}{Q_s} \quad (12)$$

5.2 Test Dilution Ratio

To determine the optimal dilution ratio necessary for a valid test, the following calculations were performed.

For diesel operation test time is set at 2 minutes and the sample flow rate is set at approximately 3 SCFM. Since there is an minimum filter fouling recommended by EPA, the approximate dilution ratio to use can be calculated to produce optimally fouled filters at the given sample flow rate and test duration.

The expected particulate concentration must be known.

For the Caterpillar 3208 assuming the expected levels are 1.0 g/bhp-hr at 210 hp, the expected amount of particulates at the end of two minutes is:

$$1.0 \text{ g/bhp-hr} \times 210 \text{ bhp} \times 0.0333 \text{ hr} = 6.9 \text{ g}$$

If we assume 450 SCFM total exhaust flow rate, the expected particulate concentration will be:

$$3.45 \text{ g/min} / 450 \text{ SCFM} = 7.7 \times 10^{-3} \text{ g} / \text{ft}^3$$

Since the recommended amount of mass accumulated is 1.3 mg/min, and the sample flow rate is 3 SCFM we would like a diluted concentration of particulates of:

$$0.0013 \text{ g} / 3 \text{ scfm} = 4.3 \times 10^{-4} \text{ g} / \text{ft}^3$$

This means the dilution ratio chosen must be:

$$D_R = \frac{7.7 \times 10^{-3} \text{ g/ft}^3}{4.3 \times 10^{-4} \text{ g/ft}^3} = 17.8$$

The dilution ratio would be set to approximately 18:1 using the butterfly valve and the exhaust ball valve. If additional control is necessary, a valve upstream of the sample pump can be used to change the sample flow rate.

These calculations provide guidelines for the particulate measurements which will be discussed in detail in Section 7.

6.0 INITIAL TESTS WITH THE DILUTION TUNNEL

Following construction of the dilution tunnel a series of tests were conducted to assess performance and repeatability. For all work summarized a normally aspirated Caterpillar 3208 diesel engine was used. Tests were conducted initially with the engine on diesel fuel, while later tests were with dual fuel. The conversion system used to allow the engine to operate on natural gas was a microprocessor based system which has been described in detail previously [7,8].

The first series of tests were concerned with assessing whether there was adequate mixing and cooling in the tunnel. A thermocouple was placed downstream of the secondary filter (see Figure 3) and the temperature was monitored closely. The dilution ratio was varied from 4.3 to 16.8. The maximum temperature observed was always below 52 C, which is the maximum allowable temperature according to the EPA test procedures.

There were no direct checks done to determine whether there was homogeneous mixing in the tunnel since to do this requires complete flow visualization capability. However the BC Research dilution tunnel has the same dimensions, flow rates and surface roughness as one used by the Cummins Engine Co. Their tunnel exhibited good homogeneous mixing, and therefore we have assumed that similar mixing exists for the BC Research dilution tunnel.

Numerous test runs were conducted to determine the repeatability of the particulate measurements. Typical results illustrating the reproducibility of the particulate measurements are shown in Figure 8. This diagram shows the good reproducibility of the particulate measurements.

As mentioned before all tests were conducted using methodology defined by the United States Environmental Protection Agency. For a given dilution ratio the experimental variation was approximately 5% when diesel fuel was used. On natural gas the scatter in the data was larger (11%). There are two reasons for this: 1) for most runs on natural gas the mass of particulates on the filter was generally below the 2.6 mg equivalent fouling specified by the EPA, so that the relative uncertainty in measuring the particulate mass was larger than for diesel operation 2) due to lower particulate levels for natural gas the sampling time was longer than for diesel. Normally longer sampling times would reduce the uncertainty, however, when longer sampling times are considered it is more difficult to ensure that the engine operating conditions are constant.

Following completion of the repeatability tests, the last sets of data were compared with the initial results.

There was no noticeable difference in particulate results from the first series of tests to the last, indicating particulate coating of the dilution tunnel was not significant. This showed that no significant restrictions were offered by particulate coating of the dilution tunnel.

To ensure that the sampling time for the tests was not prohibitively long it was necessary to perform tests at different dilution ratios. There are two factors that can effect the measured particulate emissions in the mini-dilution tunnel, namely filter temperature effects and dilution ratio effects. Suzuki et al [4] and MacDonald et al [9] have shown that the average mass concentration on the filter decreases with temperature. In their work they showed that an increase in filter temperature from 35 to 100 C reduced the mass concentration by approximately 13%. The reason for this is due to a decrease in the soluble fraction of particulate emissions with temperature. The particulate concentration also decreases with dilution ratio (filter temperature fixed) as shown by MacDonald [9]. Once again the changes in particulate concentration were due to changes in the soluble portion of the particulate sample.

For all the tests that we conducted the dilution ratio and filter temperature are not independent but rather are linked. As the dilution ratio is increased the filter temperature decreases [9]. Due to this interaction the separate effects of these two factors tend to counteract one another. MacDonald believes that this cancelling process, plus the fact that the individual effects are small is probably the reason that results from previous studies [10-13] have shown little or no effect due to dilution ratio variations.

Tests were conducted with our dilution tunnel to determine what effect dilution ratio has on particulate emissions. These results are summarized in Figures 9 and 10. It is clear from this diagram that the variation of particulate emission with dilution ratio is entirely within the experimental uncertainty ($\pm$ 11%). Therefore, we concluded that varying filter temperature did not have a large effect on the measured particulate mass, so that tests could be conducted with variable dilution ratio.

From the preliminary test data the exhaust gas densities were calculated from the concentration of the major components of the exhaust gases for both diesel and dual fuel operation. The density of exhaust gas was virtually the same for both fuels. The atomic weight of the diesel exhaust was found to be 29.2 kg/kmol for diesel and 28.5 kg/kmol for natural gas. The experimental uncertainty in these results was typically $\pm$0.2. These experimentally determined density values were used in all subsequent calculations.

7.0 EXPERIMENTAL RESULTS AND DISCUSSION

Particulate measurements were conducted for engine speeds of 1400, 1800, 2400, 2600 and 2800 rpm with loads of 40, 50, 80 and 100 % of maximum. These tests were conducted for both diesel and dual fuel operation. Numerous tests were performed for each of these operating conditions. In the interests of brevity only typical results will be presented.

The particulate emissions on a gram/bhp-hr basis are shown as a function of engine speed in Figure 11 for maximum load. It is clear from these results that the particulate emissions are considerably lower for all engine speeds while operating in the dual fuel mode. For example the diesel particulate emissions are approximately 7 times larger at 1400 rpm and 5 times larger at 2600 rpm than the dual fuel particulate emissions.

These results clearly indicate that particulate emissions on dual fuel are in fact significantly lower than for diesel operation. As such these results are very encouraging regarding compliance with upcoming US EPA particulate standards. It should be pointed out that the dual fuel conversion system varies the relative amounts of each fuel dependent on speed and load. As an example for maximum load the level of diesel substitution is approximately 85% at 1400 rpm and 75% at 2800 rpm.

The results shown in Figure 11 indicate that for engine speeds between 1400 and 2000 rpm the particulate emissions are below 0.1 g/bhp-hr. Although this appears to be less than the new EPA standard, it should not be compared because the results presented in Figure 11 are based on steady state tests while the EPA standard is based on a transient test cycle.

In Figure 12 the particulate emission is shown as a function of load with an engine speed of 1400 rpm. From this diagram it is clear that for light loads the particulate emissions for dual fuel and diesel are comparable. It should also be pointed out that the microprocessor based dual fuel conversion system used for these tests is designed to have lower values of diesel substitution at light loads. For heavy loads the particulate emissions are significantly lower on dual fuel than on diesel.

As shown in the particulate vs load curve the emissions are dependent on the amount of diesel fuel used . To determine the nature of this relationship the data was analyzed to express the particulate emission as a function of diesel flow rate. These results are shown in Figure 13. This data indicates that to minimize particulate emissions it is necessary to minimize diesel flow rate. Therefore in the design of a dual fuel conversion, from a particulate emissions viewpoint, it is necessary to maximize the substitution of diesel fuel.

8.0 CONCLUSIONS

The particulate emissions have been determined for a normally aspirated Caterpillar 3208 engine operating on diesel and dual fuel (diesel/natural gas). All tests were steady state measurements using a mini-dilution tunnel. When operating on dual fuel a microprocessor based engine control system was used. This system allowed the engine to operate with the same torque curve on dual fuel as with diesel. The dual fuel control system varied the relative amounts of diesel fuel and natural gas used dependent on speed and load.

For maximum load operation the dual fuel particulates were always lower than the diesel particulate emissions. The reduction in particulate emissions were as much as 85 % of the normal diesel emissions. For part load operation the dual fuel particulate emissions were always less than or equal to the diesel emissions.

The low particulate emissions for dual fuel operation are very encouraging in regards to meeting new EPA emission standards. However, all tests reported in this report were based on steady state test methodology, while the standard requires transient

testing. It is to be expected that similar low particulate emissions would be observed in the transient test for dual fuel operation. To verify that this is the case transient cycle testing will be required at some stage in the future.

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TABLES

TABLE 1

EPA EMISSIONS LEVELS FOR
LIGHT AND HEAVY DIESEL ENGINES

July 1, 1985
Diesel Engines Only

LIGHT DUTY VEHICLES	(passenger cars 12 people or less)	
86-085-8		0.60 g / vehicle mile 0.373 g / vehicle km
86-087-8		0.20 g / vehicle mile 0.124 g / vehicle km
LIGHT DUTY TRUCKS	(motor vehicles rated at - ó 8500 lbs GVWR ó 6000 lbs veh. curb weight ó 45 ft^2 veh. frontal area)	
86-085-9		0.60 g / vehicle mile 0.373 g / vehicle km
86-087-9		0.26 g / vehicle mile 0.162 g / vehicle km
86-088-9		0.26 g / vehicle mile 0.16 g / vehicle km
HEAVY DUTY DIESEL ENGINES	(under transient conditions)	
86-085-11		No Limits
86-088-11		0.60 g / bhp-hr
86-091-11	Urban Buses Other	0.10 g / bhp-hr 0.25 g / bhp-hr
86-094-11		0.10 g / bhp-hr

FIGURES

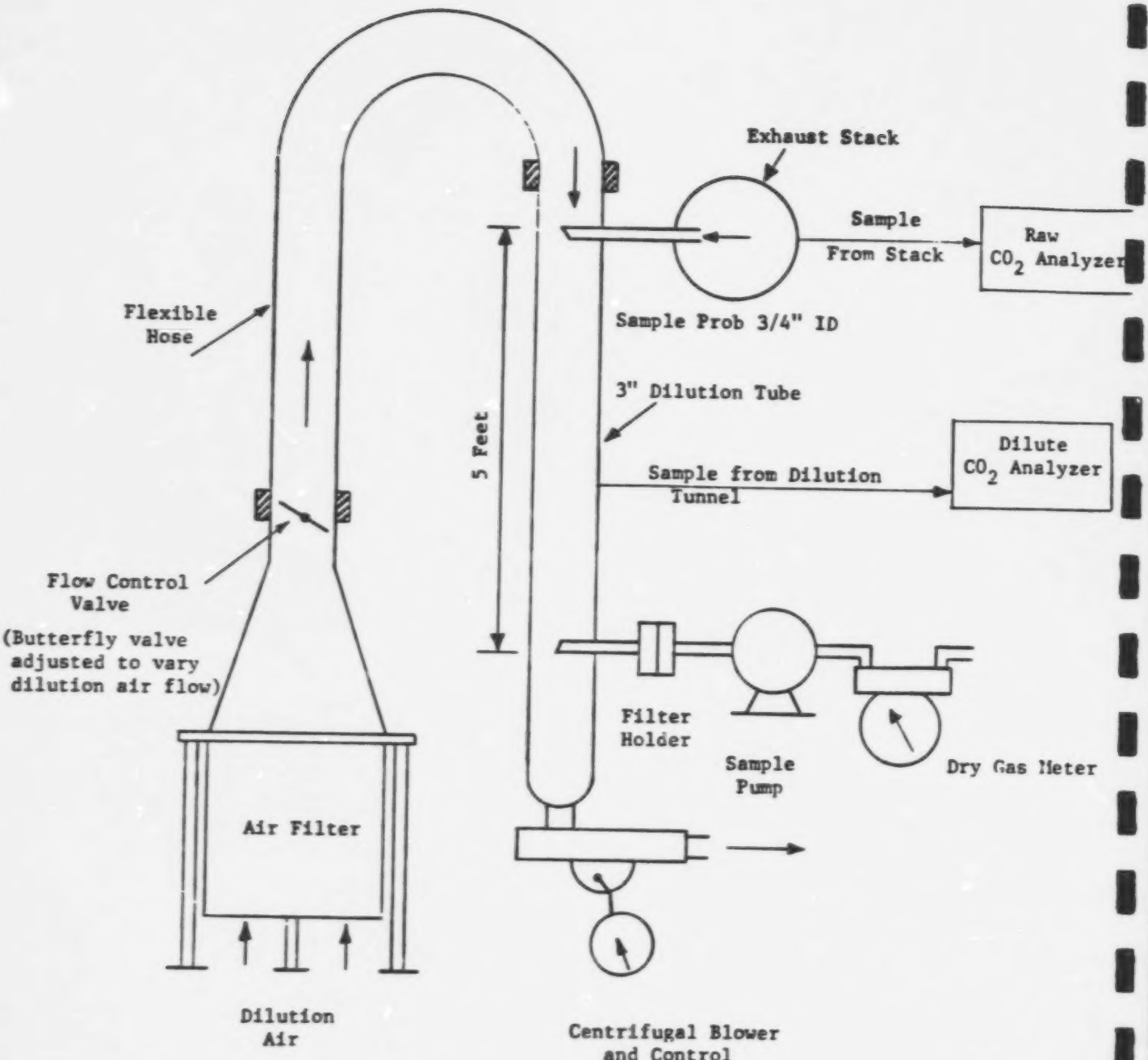

FIGURE 1

Cummins Mini-Dilution Tunnel Layout

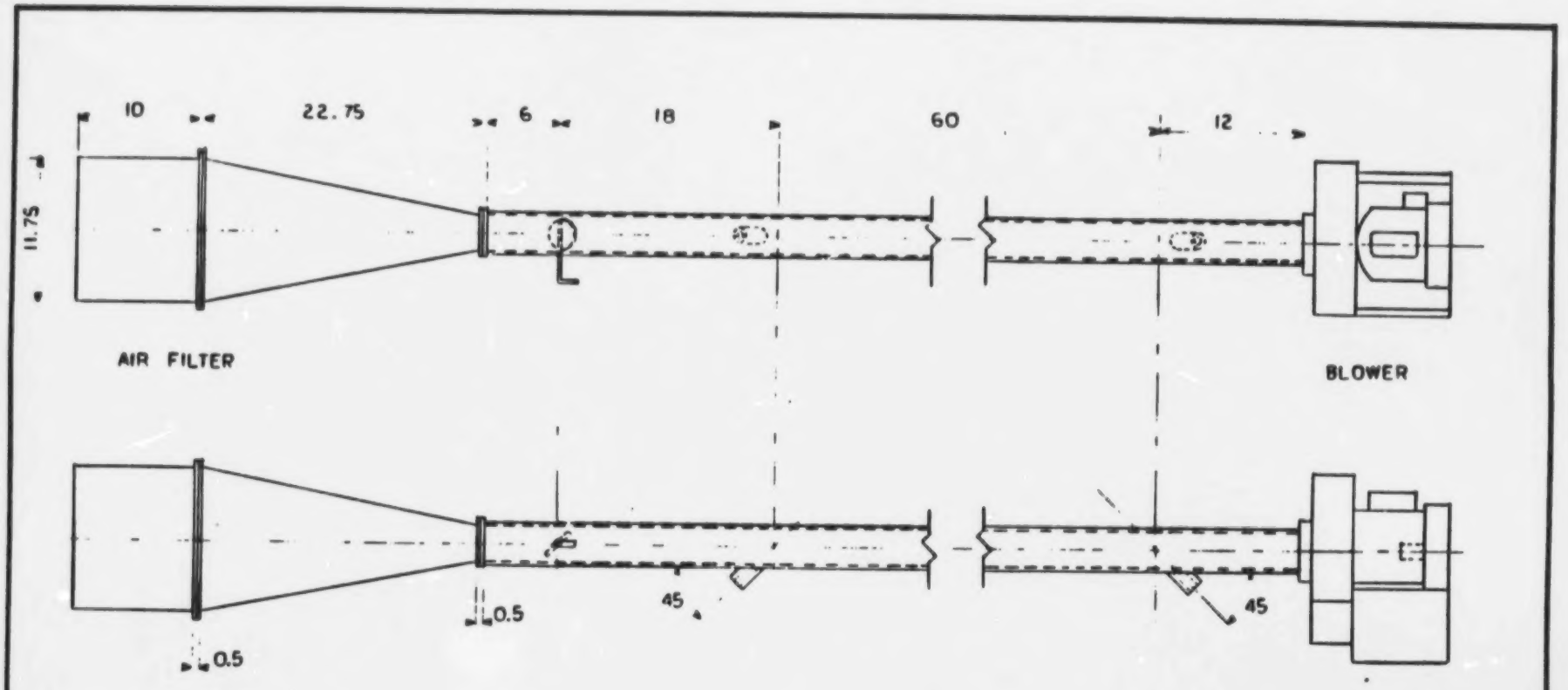

FIGURE 2

Drawing of Mini-Dilution Tunnel

DILUTION TUNNEL

SCALE: 1:8

DATE: 9 03 87

APPROVED BY:

DRAWN BY: J.P.

REVISED

DRAWING NUMBER

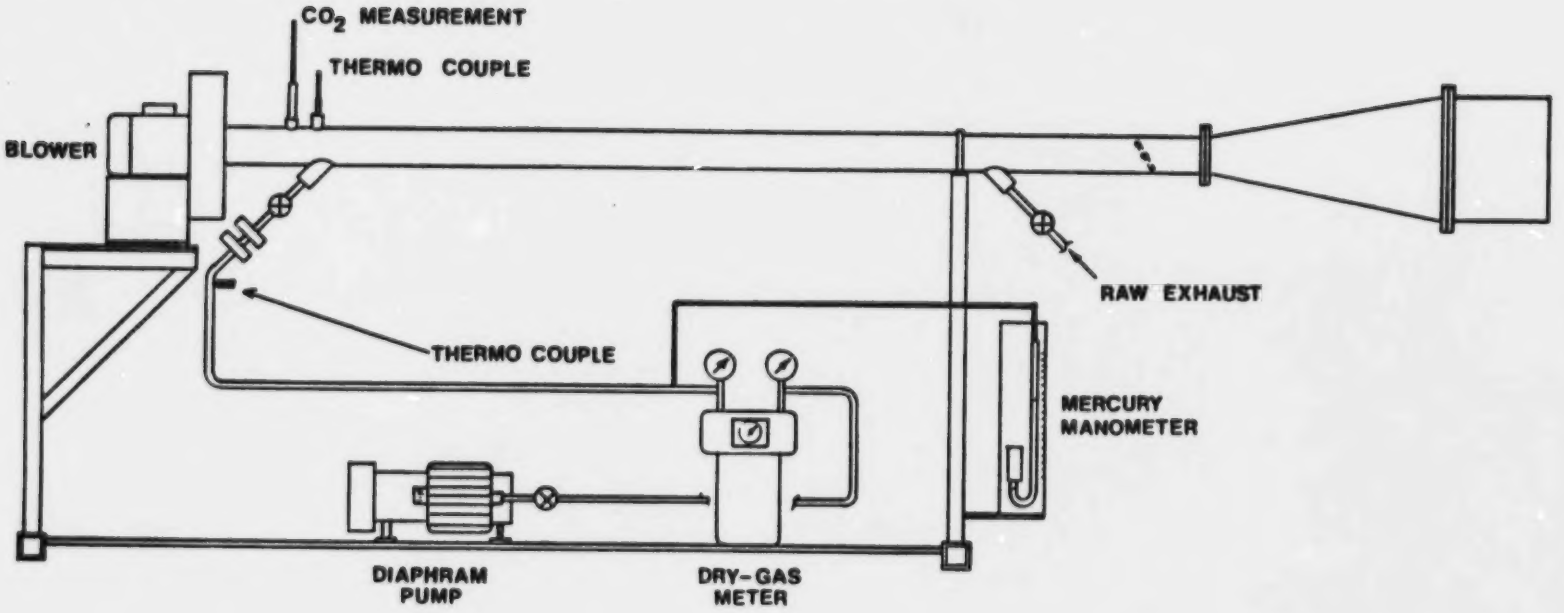

FIGURE 3

Schematic of Particulate Measurement Set-up

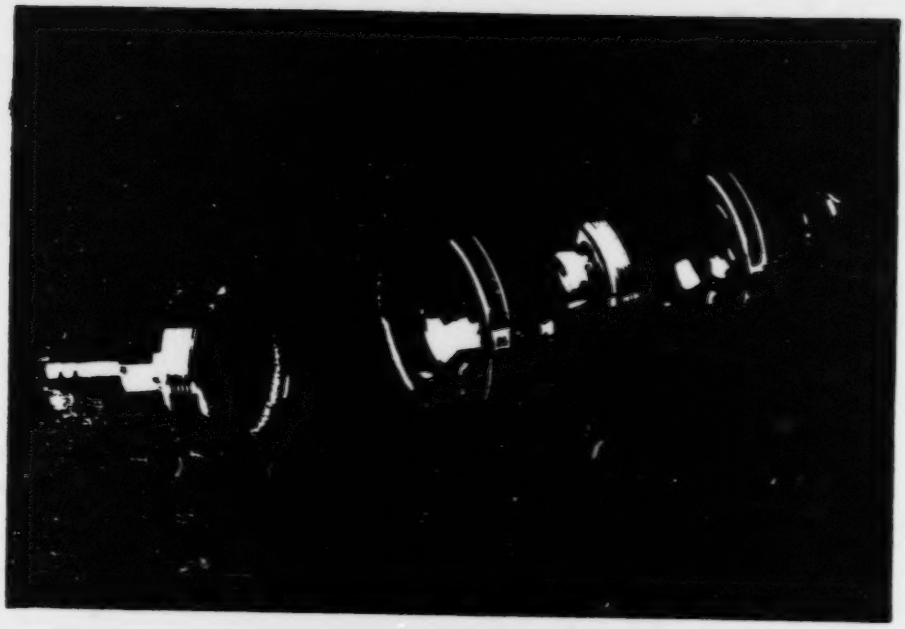

FIGURE 4

Disassembled Filter Holder Assembly

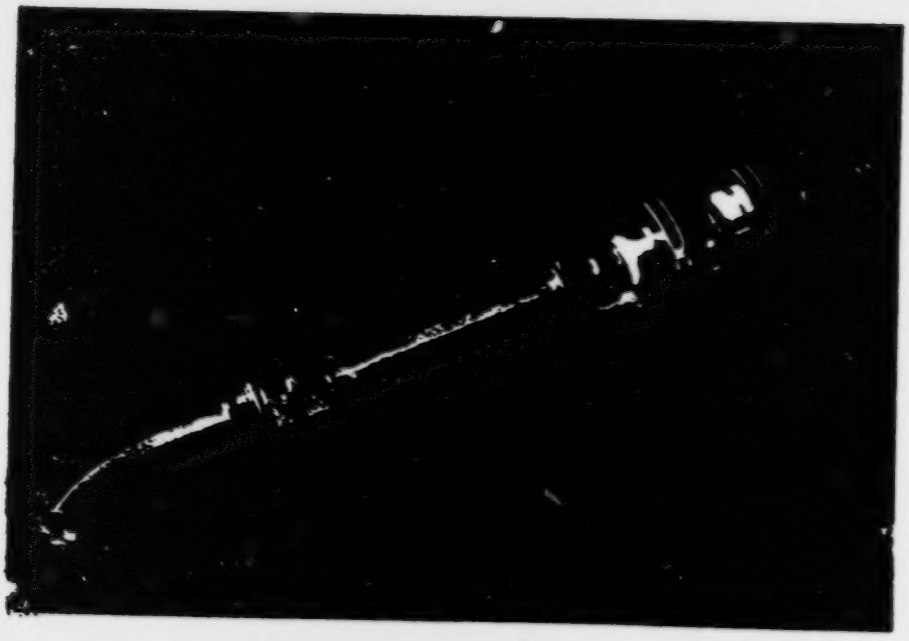

FIGURE 5

Assembled Filter Holder Assembly

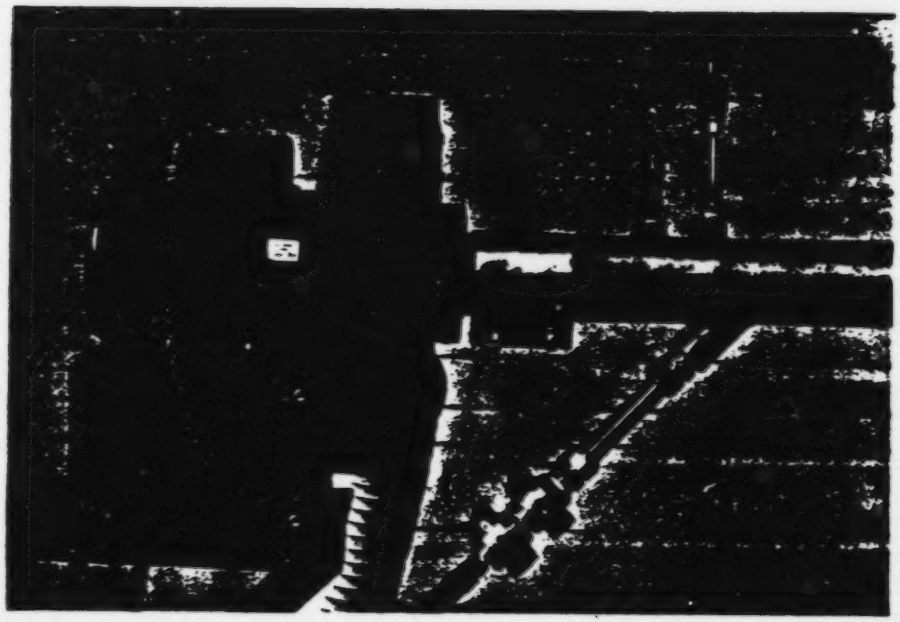

FIGURE 6

Filter Unit Inserted in the Dilution Tunnel

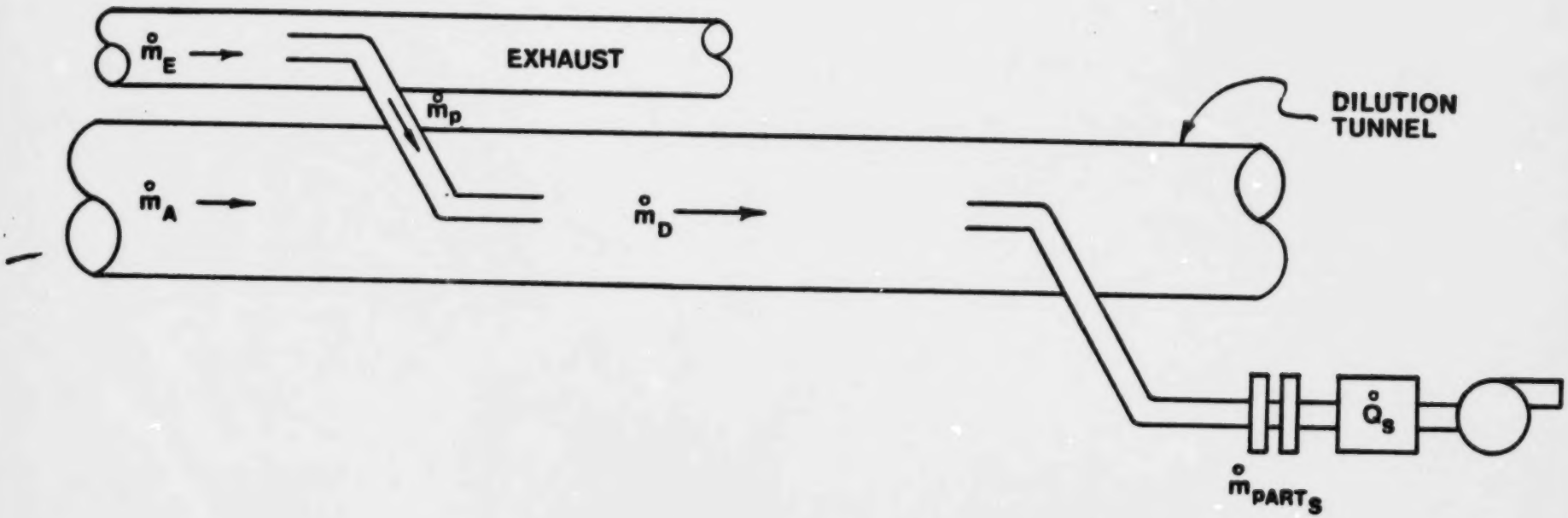

FIGURE 7

Flow Rates in Dilution Set-up

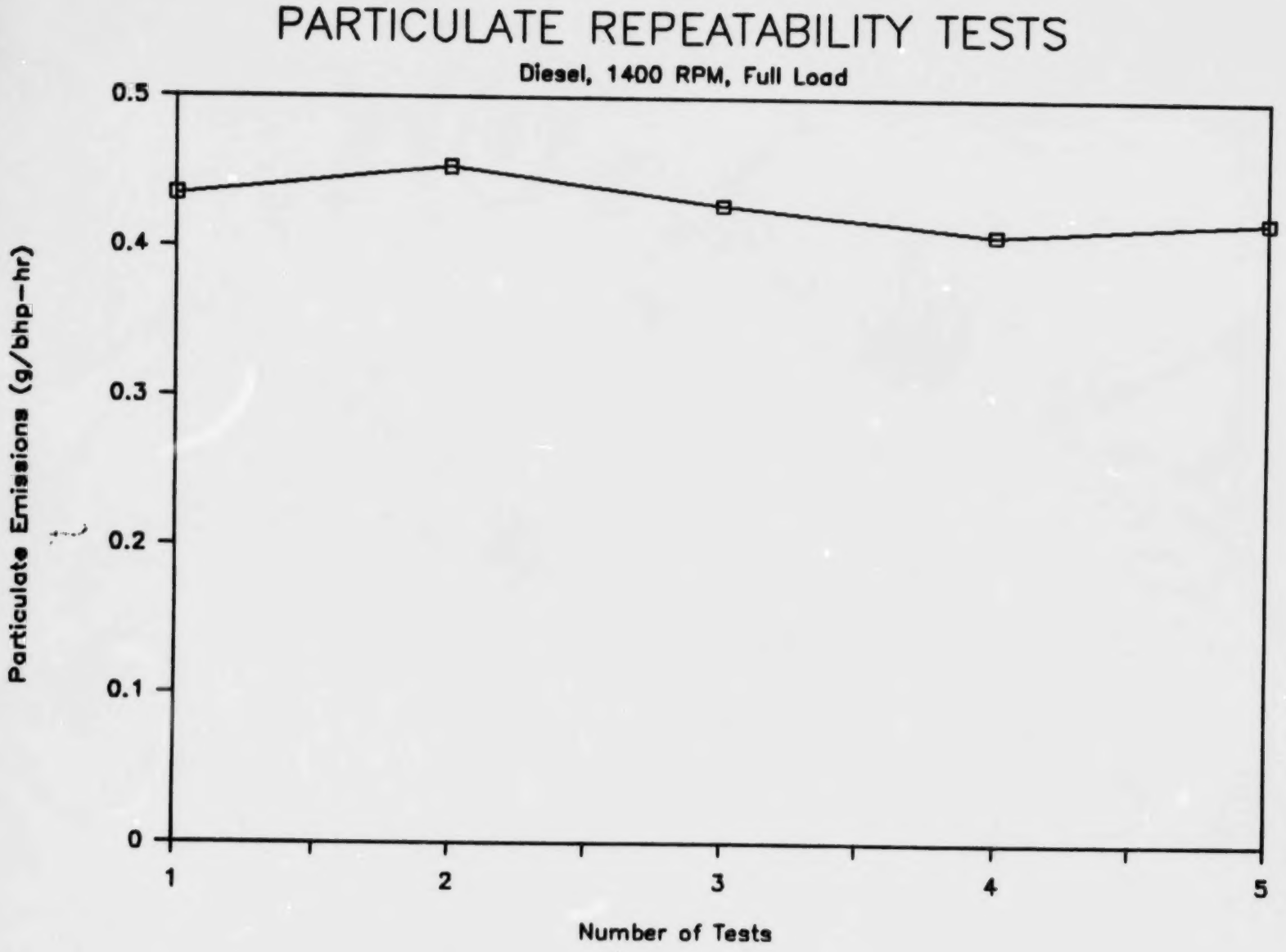
PARTICULATE REPEATABILITY TESTS
Diesel, 1400 RPM, Full Load
Particulate Emissions (g/bhp-hr)
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
Number of Tests

FIGURE 8

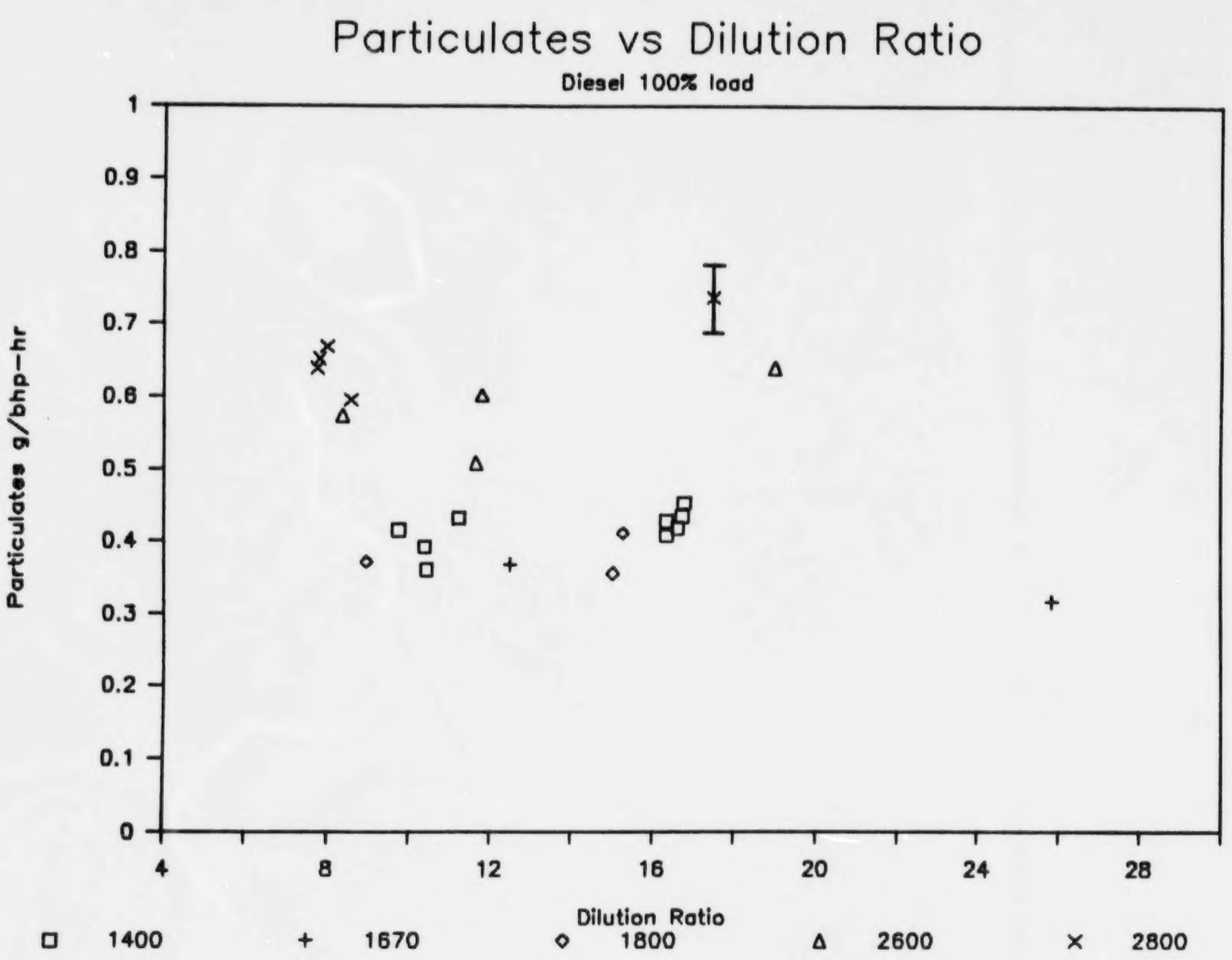
Particulates vs Dilution Ratio
Diesel 100% load
Particulates g/bhp-hr
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4
8
12
16
20
24
28
Dilution Ratio
1400
1670
1800
2600
2800

FIGURE 9

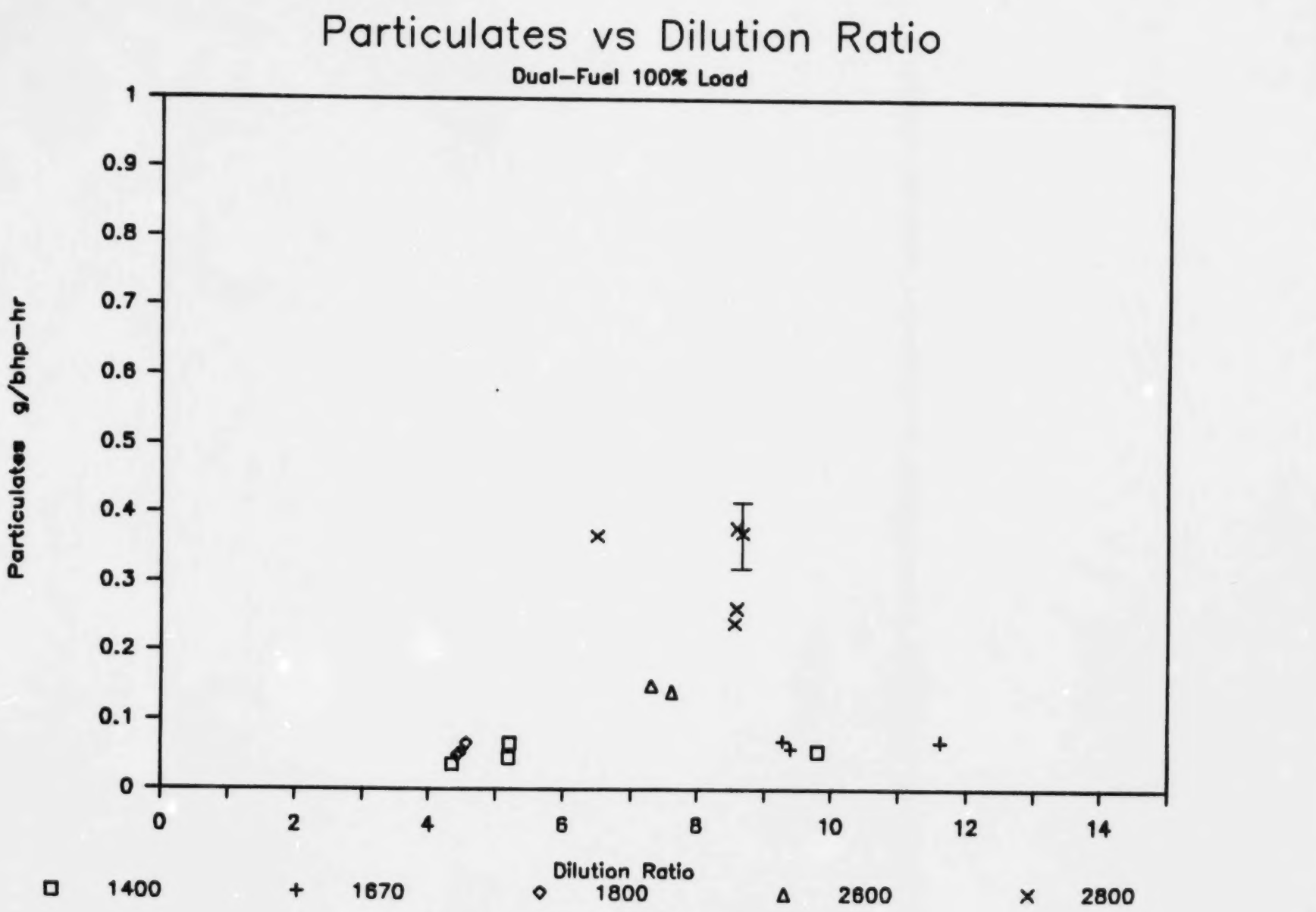
Particulates vs Dilution Ratio
Dual-Fuel 100% Load
Particulates g/bhp-hr
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
14
Dilution Ratio
1400
1670
1800
2600
2800

FIGURE 10

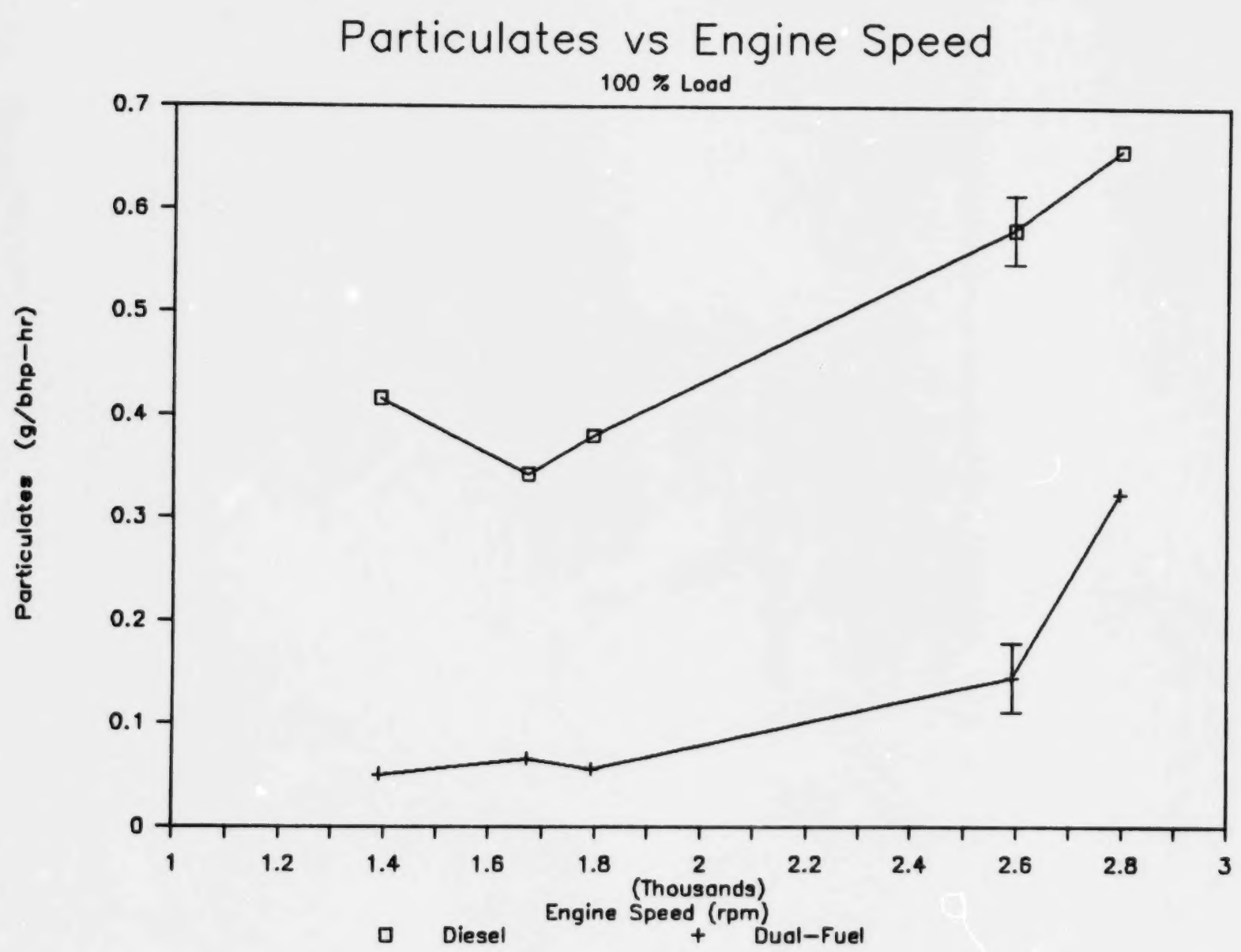
Particulates vs Engine Speed
100 % Load
Particulates (g/bhp-hr)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
(Thousands)
Engine Speed (rpm)
Diesel
Dual-Fuel

FIGURE 11

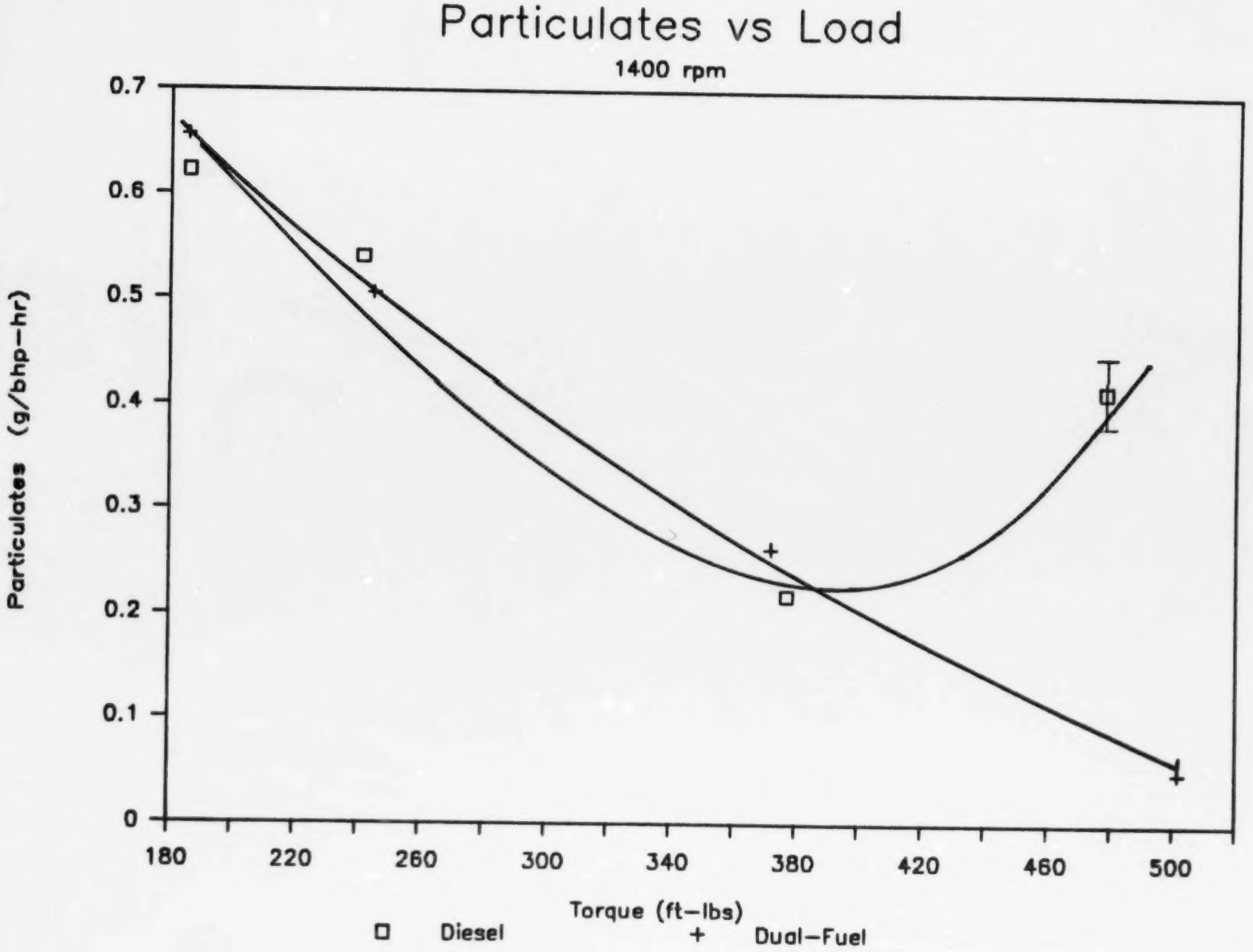
Particulates vs Load
1400 rpm
Particulates (g/bhp-hr)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
180
220
260
300
340
380
420
460
500
Torque (ft-lbs)
Diesel
Dual-Fuel

FIGURE 12

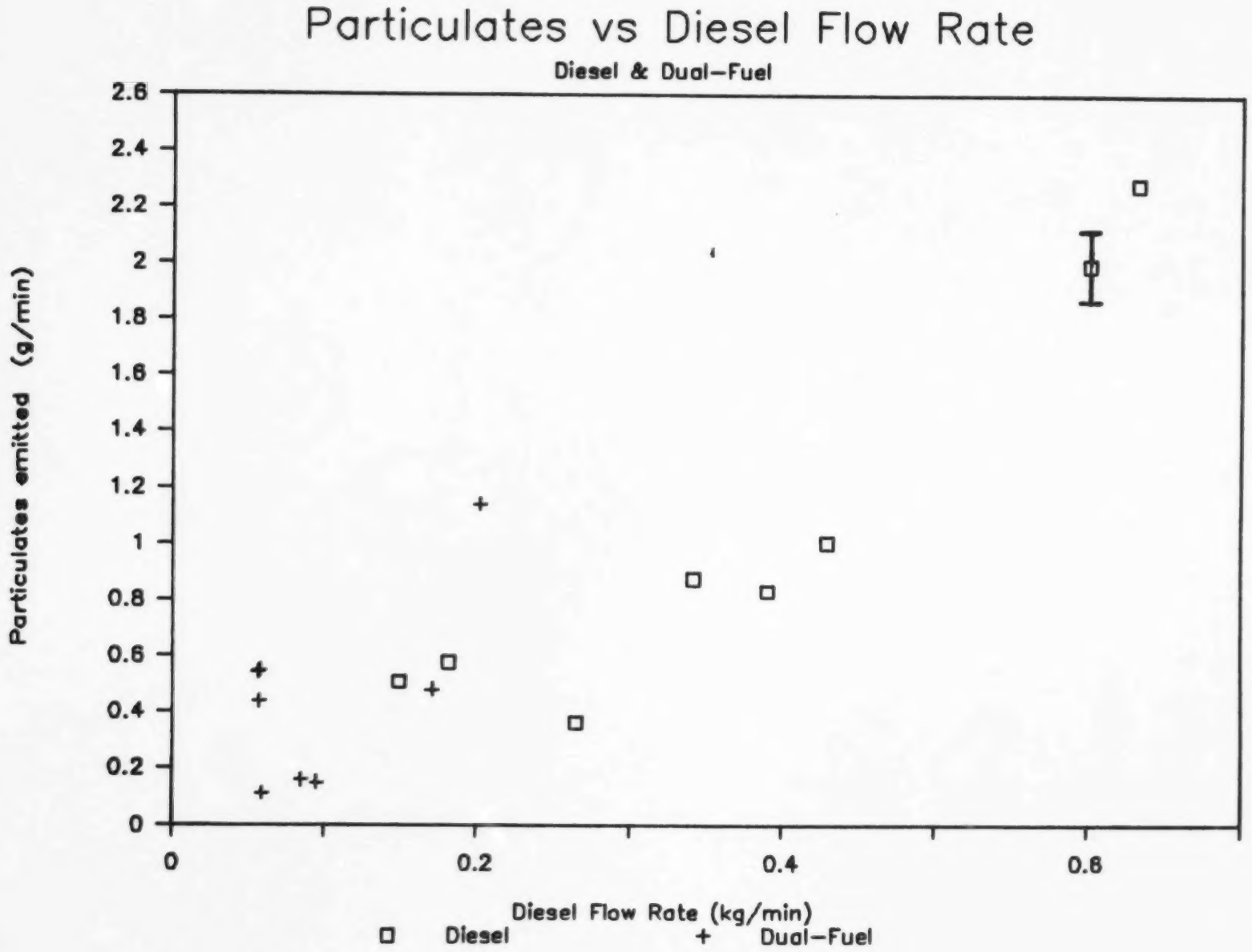
Particulates vs Diesel Flow Rate
Diesel & Dual-Fuel
Particulates emitted (g/min)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
Diesel Flow Rate (kg/min)
Diesel
Dual-Fuel

FIGURE 13